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#### How to cite:

Bashir, Imran; Taherzadeh, Shahram; Shin, Ho-Chul and Attenborough, Keith (2015). Sound propagation over soft ground without and with crops and potential for surface transport noise attenuation. *Journal of the Acoustical Society of America*, 137(1) pp. 154–164.

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Version: Version of Record

Link(s) to article on publisher's website:  
<http://dx.doi.org/doi:10.1121/1.4904502>

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# Sound propagation over soft ground without and with crops and potential for surface transport noise attenuation

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(Received 15 April 2014; revised 30 September 2014; accepted 11 November 2014)

Growing demand on transportation, road, and railway networks has resulted in increased levels of annoyance from road traffic. Optimized use of green surfaces in combination with vegetation may be desirable as a method for reducing the noise impact of road traffic in urban and rural environments. Sound propagation over soft ground and through crops has been studied through outdoor measurements at short and medium ranges and through predictions. At lower frequencies, ground effect is dominant, and there is little or no attenuation due to crops. At higher frequencies above 3–4 kHz, the attenuation in crops is dominant. It was also found that the ground effects and the influence of crops can be treated independently and can be added to obtain the total effect. Sound attenuation by crops is the result of multiple scattering between the stems and leaves, loss of coherence, and viscous and thermal losses due to foliage. The major contribution is associated with viscous and thermal losses. A model for sound attenuation by vegetation is proposed. Insertion losses for a typical road traffic noise source have been calculated that result either by replacing hard ground with different types of acoustically soft ground or by growing crops along the road sides. © 2015 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4904502>]

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Pages: 154–164

## I. INTRODUCTION

Although the possibility of traffic noise attenuation due to vegetation such as leaves, shrubs, bushes, and trees near roads has received attention during the last 40 years, there have not been many publications concerning the propagation of sound through crops. Aylor<sup>1,2</sup> has studied sound transmission loss through various crops, bushes, and trees including dense corn, hemlock, red pine trees, hardwood brush, and dense reeds in water. Aylor<sup>1</sup> suggested that although adding ground effect to the attenuation due to leaves and stems to obtain the total attenuation might be reasonable, it might not always be accurate due to multiple scattering by stems, leaves, and twigs causing some additional interaction with the ground. Aylor<sup>1</sup> considered first whether the sound attenuation due to vegetation is due to viscous and thermal dissipation between the fluid media and plant surfaces. However, he found that the attenuation due to viscous and thermal losses calculated for a given vegetation density is less than the measured attenuation. Aylor<sup>1</sup> argued that the extra energy loss observed is due to multiple scattering effects within the vegetation. It was concluded that the attenuation is directly proportional to vegetation density and that foliage attenuates the sound at higher frequencies. Aylor<sup>2</sup> extended his work to study the sound propagation through reeds planted in water because sound reflection due to a water surface (assumed to be acoustically hard) can be determined very accurately thereby enabling ground effect to be

separated from the vegetation effect. Aylor<sup>2</sup> concluded that to maximize the sound attenuation due to the vegetation, it should be planted densely with high leaf area per unit volume. Also Aylor<sup>2</sup> has suggested an empirical relationship between attenuation and foliage characteristics.

Martens<sup>3</sup> has investigated sound propagation through vegetation and its effects in a laboratory. Although, like Aylor, Martens found that the attenuation due to plants is at higher frequencies and that vegetation behaves as a low pass filter (attenuation between 2 and 8 kHz), he suggested that Aylor's empirical prediction method did not fit his measured data. Subsequently, Aylor<sup>4</sup> explained that the excess attenuation measured by Martens<sup>3</sup> was normalized by total plant biomass, whereas in his study,<sup>1,2</sup> excess attenuation was normalized using the leaf area per unit volume. When Martens' results were normalized using leaf area per unit volume in the same way, the agreement was better. According to Aylor, leaf area per unit volume is more important than the total plant biomass for noise attenuation. However, according to Martens,<sup>3</sup> the total biomass of vegetation is more important. Using a laser-Doppler-vibrometer, Martens and Michelsen<sup>5</sup> studied the vibration of plant leaves in response to acoustic energy. The sound energy absorbed by each leaf through vibration is very small. However, for a full grown tree, the individual leaf attenuations add together to give a significant overall effect.<sup>5</sup> Subsequently Martens *et al.*<sup>6</sup> found that the size of the leaf is an important parameter for the reflection of sound, i.e., the bigger the leaf size, the larger will be the acoustic reflection. The second important parameter for sound reflection is the mass of the leaf, especially at high frequencies when the wave-length is less than the leaf size. They reached the same conclusion as Aylor<sup>1,2</sup> that plants with dense foliage and larger leaf sizes give higher sound attenuation.

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Price *et al.*<sup>7</sup> have measured sound attenuation due to woodlands and compared the resulting data with the predictions of a model obtained by summing the separate contributions of the ground, the trunks, the branches, and the foliage. While the simple addition of ground effect predictions to single scattering predictions based upon trunk size and density did not give good agreement at high frequencies, a semi-theoretical model including a phenomenological adjustment for foliage effects improved the agreement with measured data. Huisman and Attenborough<sup>8</sup> have measured excess attenuation spectra through pine forest at different ranges of between 10 and 100 m. Up to 1 kHz where the ground effect dominated, the excess attenuation was predicted successfully using a two parameter impedance model. At higher frequencies, the data differed from predictions of ground effect alone and show more attenuation due to scattering by trunks, branches, and viscous losses through the vegetation. The observed high frequency attenuation was modeled as energy loss due to multiple scattering inside the vegetation, and it is added to the attenuation due to ground. However, because the agreement between data and prediction remained poor, it was concluded that the interaction between the ground effect and multiple scattering is more complicated than a simple addition. Fang and Ling<sup>9</sup> investigated noise attenuation by 35 different tree belts and found that the attenuation depended on the width, height, length, and density of tree belts. Large shrubs and densely populated tree belts were found to give more than 6 dBA attenuation, medium size shrubs and tree belts attenuated the sound by between 3 and 6 dBA, and sparsely distributed tree belts and shrubs attenuated the sound by less than 3 dBA. The width of vegetation was found to be the most important factor in that the greater the vegetation width, the greater the pathway of sound through the vegetation resulting in higher sound absorption and diffusion. Also when the tree belt was longer, it was considered that acoustic waves would diffract and scatter more resulting in higher attenuation. In all of the vegetation belts examined, the shrubs were considered to be the most effective in reducing noise due to scattering from dense foliage and branches at lower source-receiver heights. At higher source-receiver height, trees were considered to provide good attenuation due to sound diffusion and absorption processes. Thus it was concluded that tree belts and shrubs should be planted together to provide best attenuation performance.<sup>9</sup> Tarrero *et al.*<sup>10</sup> carried out an experimental investigation of the sound attenuation in different types of forests with different tree densities, different trunk diameters, and both deciduous and evergreen leaves. The measured data at several source-receiver distances showed that the trees have a noticeable effect on sound attenuation at longer distances of more than 40 m. However, if the trees are planted densely, then the attenuation effect due to trees can be seen at shorter ranges. The predictions of the attenuation due to vegetation were carried out using a simple scattering model taking account of the reduced coherence between the direct and reflected sound field.

Attenborough *et al.*<sup>11</sup> studied sound propagation through crops at short, i.e., 1 m, and medium ranges, i.e., 10 and 20 m. Excess attenuation data over 0.55 m high wheat crops

show that the presence of crops appears to influence the coherence of the ground-reflected sound. Due to the loss of coherence, the excess attenuation maximum gets distorted. Attenborough *et al.*<sup>11</sup> have found that measured data through vegetation and predictions for ground effect alone show good agreement up to 1 kHz. At higher frequencies, because the data have significantly different magnitudes and frequency dependence to those predicted by ground effect alone, it is proposed that sound attenuation is due to scattering of sound by trunks and branches plus the attenuation of sound by viscous losses in the foliage.

Using a three-dimensional (3D) finite-difference-time-domain method, Van Renterghem *et al.*<sup>12</sup> have investigated predictions of noise propagation through 15 m deep tree belts. They consider that noise attenuation by tree belts occurs due to three mechanisms. The first is the scattering of sound by trunks, branches, twigs, and leaves; the second is the sound absorption by vegetation due to leaves vibration and viscous-thermal boundary layer effects, and the third is sound attenuation due to ground effect. The presence of a forest floor gives significantly more low frequency attenuation than typical grassland. The insertion loss due to a tree belt increases with increase in tree stem diameter and decrease in spacing between the trees. The traffic noise attenuation also increases with the increase in tree heights. It was concluded that in addition to other attenuation mechanisms such as ground effect, 2–3 dB more insertion loss can be obtained by careful arrangements of tree belts.

Through laboratory measurements and predictions, Taherzadeh *et al.*<sup>13</sup> have studied sound transmission through periodic, perturbed and randomly arranged vertical cylinders placed on an acoustically hard (MDF board) and acoustically soft (felt-MDF) ground, respectively. They found that the ground effects and sonic crystal effects are additive and that for low filling fractions, a perturbed cylinder array leads to better overall insertion loss than a regular one.

Section II describes the measurement system and experimental procedures. Section III presents measured level difference data through winter wheat crops. Prediction methods for sound propagation through crops are described in Sec. IV. Comparison between data and predictions are presented in Sec. V. Section VI gives the predicted insertion losses by replacing hard ground with different soft ground surfaces along with the added attenuation due to growing crops. Conclusions are drawn in Sec. VII.

## II. MEASUREMENT SYSTEM AND ARRANGEMENTS

The acoustical characterization of ground growing crops and the propagation of sound through crops have been studied using vertical and horizontal level difference measurements techniques, respectively (see Fig. 1). The level difference between vertically separated microphones is calculated by subtracting the measured sound pressure level (SPL) spectrum at the upper microphone from that measured at the lower microphone. The horizontal level difference is calculated by subtracting the SPL measured at desired location from the SPL measured at a reference microphone, which is nearest to the source.



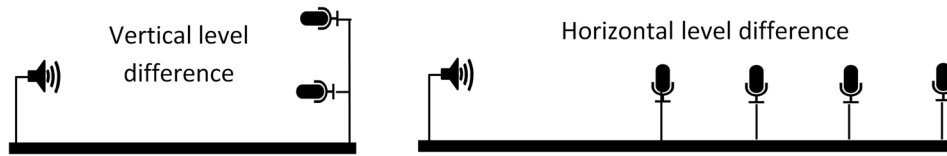


FIG. 1. Schematics of vertical and horizontal level difference measurement arrangements.

The measurement system used in the field consists of a laptop installed with MATLAB data acquisition tool box, connected to 16 bit National Instruments-USB 6259 data acquisition box (NI-DAQ). The NI-DAQ box provides interface between digital and analog world. A MATLAB code has been written for generating a digital signal, communicating and controlling NI-DAQ, acquiring the measured input, and storing it in a digital form. The data acquisition board is connected to the speaker through an audio amplifier. Two types of speaker, the B&K type 4295 point source and a Tannoy speaker were used to emit white noise. Between two and four microphones were used for data collection depending on the specific scenario. A series of measurements have been made using measurement system described in the preceding text in a field of 0.45–0.55 m high winter wheat crops at Butt Close experimental farm in Woburn Sands, Bedfordshire, UK, operated by Rothamsted Research. Some data were collected also over other types of crops such as rape-seed and willow crops. Measurements were carried out during summer (June to September) 2011 and in May and June 2012.

### III. DATA ACQUISITION, AND ANALYSIS

#### A. Short range data (vertical level difference)

Initial measurements at Butt Close site showed that the acoustical properties of a ground surface growing crops are different from the same type of ground with no crops. The measured spectra obtained over crops using either vertical or horizontal level difference measurement technique revealed two effects. The first is an interference effect (ground effect), and the second is attenuation due to the presence of the crops. Henceforth attenuation due to crops is called the “crops effect.” To separate ground effect from the crops effect, it is important to know the precise acoustical properties of ground. Within a small patch with dimensions  $1.88 \text{ m} \times 1.84 \text{ m}$ , vertical level difference measurements were carried out inside crops with different geometries and at different positions as shown in Fig. 2(a) (upper). After that the selected patch was cleared by carefully removing the stems of the crops without disturbing the ground. The cleared patch is shown in Fig. 2(a) (bottom). The measurements were carried out before and after clearing the selected area on the same day. Consequently two data sets were available, i.e., level difference spectra including both ground and crops effects and level difference spectra due to ground effect only. Figure 2(b) compares the measured level difference spectra with and without crops for a source height of 0.3 m, upper and lower microphone at height of 0.3 and 0.15 m with a horizontal separation of 1.0 m. This geometry, called Geometry E, is given in Fig. 2(b). It is concluded from these data that there are no measurable effects of crops

over a range of 1 m. The stems of the wheat crops are very thin with a mean stem diameter of 2.63 mm. Measurements made at similar patches with winter wheat crops and rape seed crops (not presented here) confirm that crops do not influence sound propagation over a range of 1 m. These data are used later for characterization of ground growing crops.

#### B. Medium range data (horizontal level difference)

Horizontal level difference spectra have been measured by placing the reference microphone at a horizontal distance

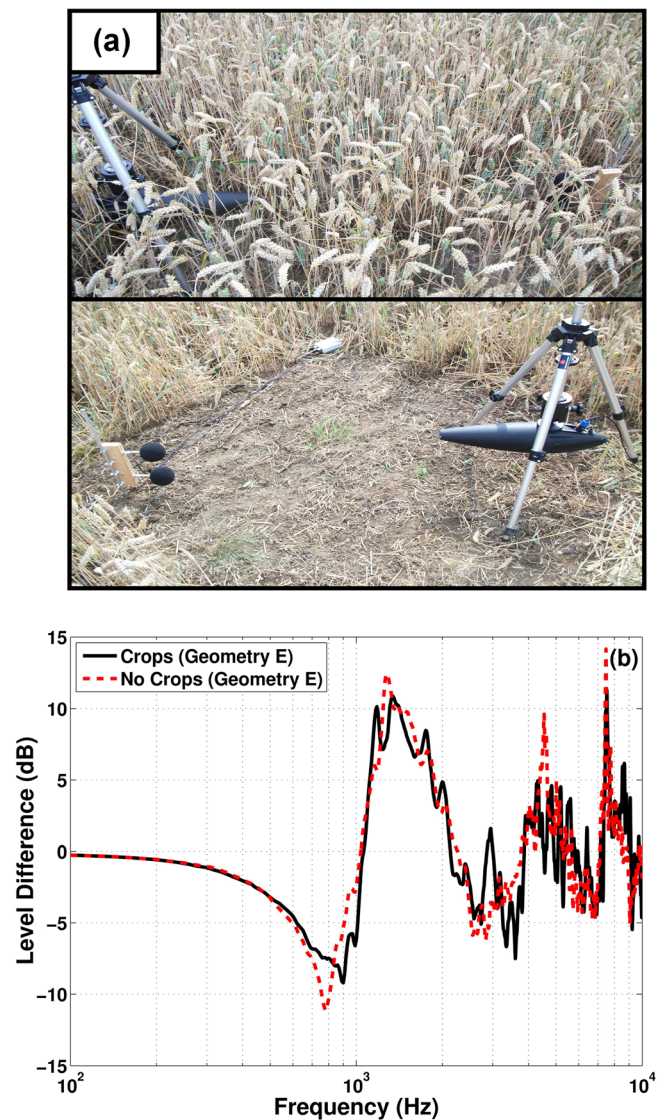


FIG. 2. (Color online) (a) Photographs of site used for short range crops measurements with crops and without crops. (b) Level difference spectra measured over ground with 0.5 m high crops and without crops, source height, 0.3 m; upper microphone height, 0.3 m; lower microphone height, 0.15 m; source-receiver separation, 1.0 m (termed “geometry E” in the legend).

of 1.0 m from the Tannoy source and further microphones at the same height as the source but at distances of 2.5, 5.0, 7.5, and 10.0 m, respectively (see Fig. 3). The measured average winter wheat crops height was between 0.45 and 0.55 m. Measurements were carried out at several source and receiver heights. However, the microphones and source were always inside the crops. Measurements were carried out by placing source and receivers at equal heights of 0.2, 0.3, and 0.4 m. In this paper, only the measured data for a height of 0.3 m are presented because similar results were obtained and similar conclusions were drawn for all three geometries. Measurements were carried out during dry conditions in August 2011, wet conditions in May 2012 when the crops were greener and intermediate conditions in June 2012. Figure 3 shows photographs of the crops during the different outdoor measurements.

Figures 4(a), 4(b), 4(c), and 4(d) show measured level difference spectra between the reference microphone at a distance of 1.0 m and microphones at 2.5, 5.0, 7.5, and 10.0 m, respectively, from the source. The spectra for different distances were normalized in the sense that the attenuation due to geometrical spreading were subtracted from data. Hence the “corrected horizontal level difference” spectra here refer to attenuation in excess of that due to wavefront spreading. Background noise recordings indicated that the sound levels with the source on were above the background level up to 9 kHz at distances up to 7.5 m and up to 7 kHz at a distance of 10 m. Therefore the spectra measured at 10 m range may not be accurate above 7 kHz. However, this does not invalidate any of the conclusions reached. Level difference data at a range of 7.5 m are missing for the measurement exercise carried out in June 2012 due to time and weather constraints. The source and the receivers were placed at equal heights of 0.3 m above ground. Figure 4 compares the measured spectra over crops during different times of the year. It is concluded from the longest range data [see Fig. 4(d)] that dry crops with fallen leaves [August 2011, see Fig. 3(a)] give the least sound attenuation at frequencies above 3 kHz. Whereas the green crops with leaves [May 2012, see Fig. 3(b)] give the most sound attenuation at these frequencies. The crops in an intermediate state [June 2012, see Fig. 3(c)] produced high frequency attenuation

spectra lying between the other two. Similar conclusions can be drawn from data at other ranges, i.e., 2.5, 5.0, and 7.5 m. The data measured over greener crops (May 2012) show more scattering at high frequencies than the less green crops (June 2012 and August 2011). Comparisons of Figs. 4(a)–4(d) suggest that as the propagation path for the sound propagation through the crops is increased, the attenuation and scattering due to crops is increased. Level difference data measured over crops at different times of the year also show spectral differences between 1 and 3 kHz, where the main ground effect maximum occurs [see spectra between 1 and 3 kHz in Figs. 4(a)–4(d)]. These spectral differences may be due to the difference in ground effect because the measurements were carried out at different locations and at different times of the year, under different weather and temperature conditions. Also the presence of crops influences the coherence between the direct and ground-reflected sound causing the ground effect maxima to become shallower. The loss of coherence may be another reason for the spectral differences between 1 and 3 kHz. This is also evident from the data as the greenest crops [see Figs. 4(a)–4(d), May 2012] provide maximum scattering and loss of coherence which result in the shallowest ground effect. Other measurements (not reported here) that have been carried out with several source and receiver heights give similar results.

#### IV. MODELS TO PREDICT ATTENUATION THROUGH CROPS

The major sound attenuation factor at high frequencies is due to viscous and thermal losses at foliage surfaces. The magnitude of the attenuation due to viscous and thermal losses and its frequency range depends on leaf size, vegetation density, stem diameter, and the length of the propagation path through the crops. The attenuation due to viscous and thermal losses can be predicted using an empirical formula [see Eq. (1)] based on Aylor’s data.<sup>2</sup> The viscous and thermal losses can be added to attenuation due to multiple scattering [see Eq. (2)] and effects due to loss of coherence to obtain the overall effect [see Eqs. (3)–(9)]. The multiple scattering and loss of coherence contribute little to overall attenuation.

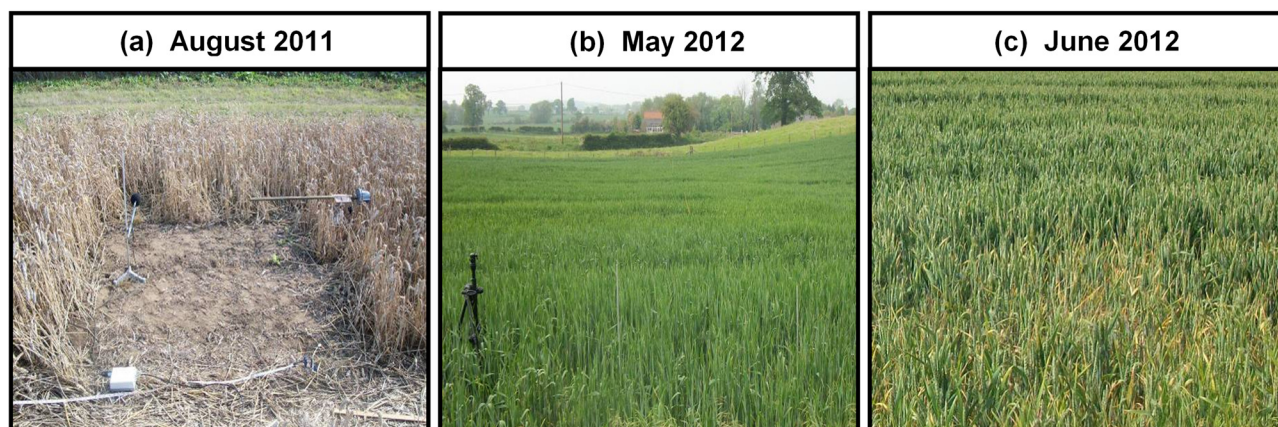


FIG. 3. (Color online) Photographs of measurements over crops at Woburn Sands at different times (a) August 2011; (b) May 2012; (c) June 2012.



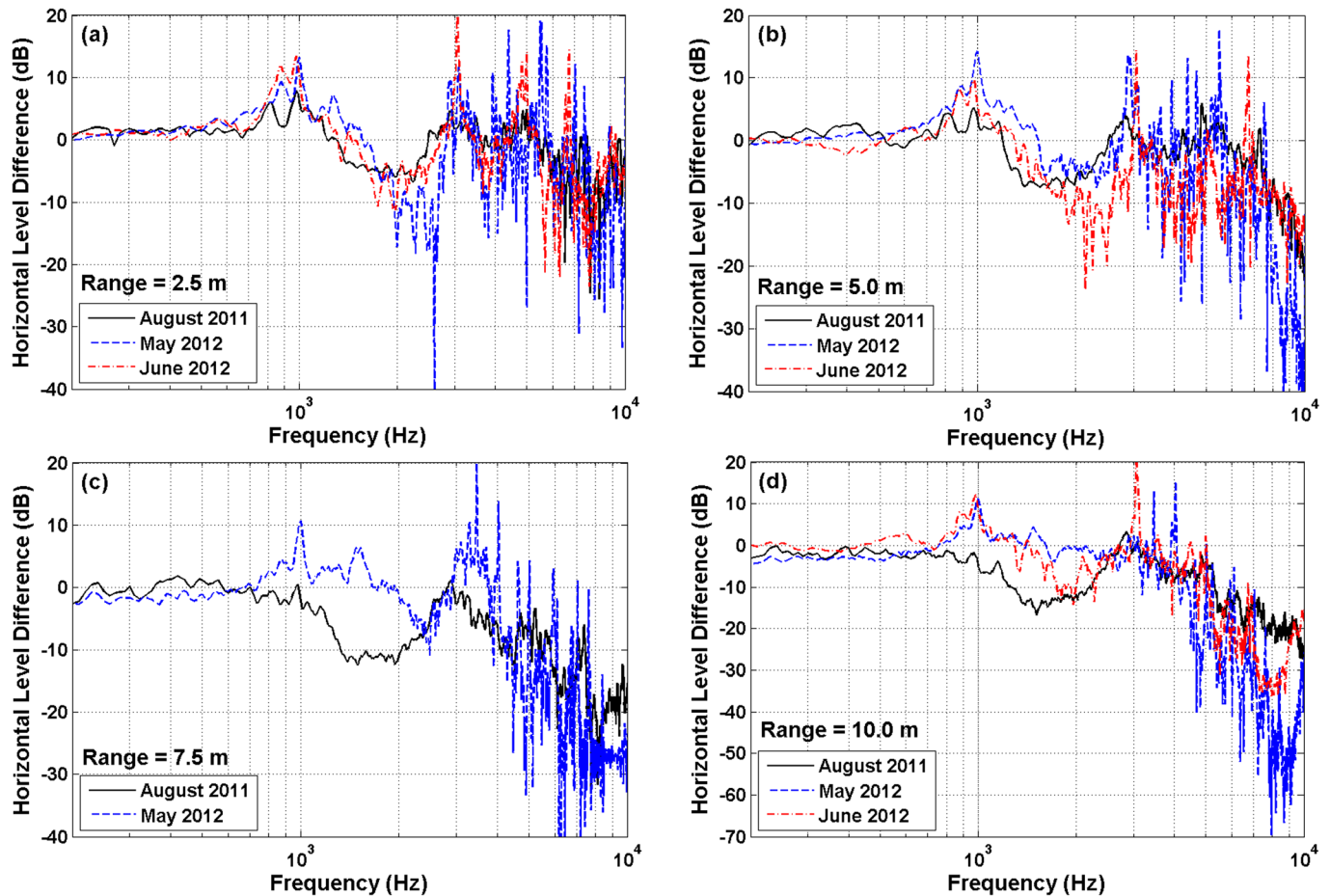


FIG. 4. (Color online) Spectra of the difference in levels measured by receivers at 1.0 m and (a) 2.5 m, (b) 5.0 m, (c) 7.5 m, and (d) 10.0 m from the source (source and receivers 0.3 m above ground) over winter wheat crops at different times of the year.

#### A. An empirical model (viscous and thermal loss due to foliage)

Aylor<sup>2</sup> has suggested that there is a relationship between a normalized excess attenuation, i.e., the attenuation in excess of that due to ground effect divided by the square root of the product of foliage area per unit volume and the scattering parameter (which is the product of wave-number and a characteristic leaf dimension). Attenborough *et al.*<sup>14</sup> have fitted Aylor's data<sup>1,2</sup> for normalized excess attenuation obtained through reeds and corn (with two leaf sizes) using the formula,<sup>14</sup>

$$\frac{EA(\text{dB})}{\sqrt{FL}} = 3[1 - \exp(0.3 - 0.5(ka))], \quad ka > 0.6, \quad (1)$$

where  $EA(\text{dB})$  represents the excess attenuation in dB.  $F (\text{m}^{-1})$  is the foliage area per unit volume,  $L$  is the length of the propagation path,  $k$  is the wavenumber  $= 2\pi f/c$ ,  $f$  and  $c$  being the frequency and adiabatic sound speed in air, respectively, and  $a$  is the mean leaf width (see Fig. 5). The lower limit on  $ka$  is required to avoid negative values of  $EA$ . For example, this implies a low frequency limit of around 1 kHz for a mean leaf width of 0.032 m and a low frequency limit of about 100 Hz for a mean leaf width of 0.3 m.

#### B. Multiple scattering model

A total of 414 winter wheat stems were cleared from the  $1.88 \text{ m} \times 1.84 \text{ m}$  area mentioned earlier. The mean diameter

of the stems was 2.63 mm with a standard deviation of 0.78 mm. The stems have been modeled as randomly located vertical rigid cylinders having a distribution of diameters with the measured mean and standard deviation and the corresponding insertion loss has been calculated using multiple scattering theory (MST).<sup>13,15</sup> Figure 6 shows MST predictions for a random distribution of 414 vertical cylinders with

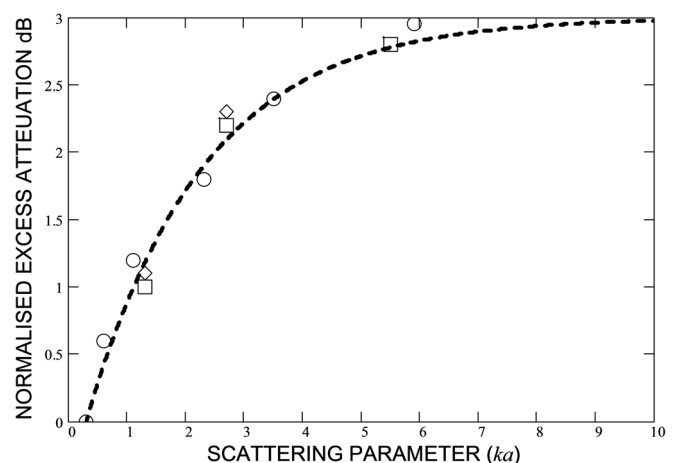


FIG. 5. Data for normalized excess attenuation  $[dB / \{( \text{foliage area per unit volume, } F ) \times ( \text{propagation path length, } L ) \}]$  through reeds (open circles) with mean leaf width 0.032 m and corn (boxes  $F = 3 \text{ m}^{-1}$ ; diamonds  $F = 6.3 \text{ m}^{-1}$ ) with mean leaf width 0.074 m and a fitted curve [Eq. (1)].

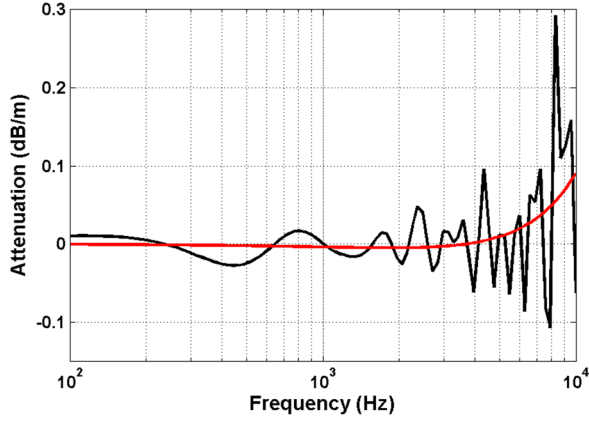


FIG. 6. (Color online) Averaged attenuation due to 20 different random realizations as a function of frequency predicted through 414 randomly located parallel rigid cylinders with mean diameter 0.263 mm and a smooth polynomial curve fit.

a mean diameter of 2.63 mm. The curve shown in Fig. 6 was obtained after averaging 20 different random realizations. To obtain an average effect due to random scatterers, a smooth polynomial curve has been fitted also. Nevertheless even including the oscillations, the overall effect is small.

The fitted polynomial curve is given by

$$IL = a_2 f^2 + a_1 f + a_0, \quad (2)$$

where  $a_2 = 1.44 \times 10^{-9}$ ,  $a_1 = -5.34 \times 10^{-6}$ , and  $a_0 = -1.26 \times 10^{-4}$ .

The resulting predictions of attenuation due to scattering in  $\text{dB m}^{-1}$  have been added to the predicted level difference due to ground effect. The comparisons between predictions and data indicate that while (reverberant) multiple scattering by the stems can account for part of the extra attenuation in the wheat crop, it does not account for all of it.

### C. Modeling for loss of coherence

Another potential effect of scattering by vegetation is to reduce the coherence between direct and ground-reflected sound, i.e., to weaken the constructive and destructive interference responsible for the ground effect. This is similar to the effect of turbulence.<sup>11</sup> The influence of turbulence on propagation from a point source near the ground can be calculated from<sup>14</sup>

$$\langle p^2 \rangle = \frac{1}{R_1^2} + \frac{|Q|^2}{R_2^2} + \frac{2|Q|}{R_1 R_2} \cos[k(R_2 - R_1) + \theta]T, \quad (3)$$

where  $\theta$  is the phase of the spherical wave reflection coefficient, ( $Q = |Q|e^{i\theta}$ ) (a function of source and receiver geometry and ground impedance<sup>16</sup>), and  $T$  is the coherence factor determined by the turbulence effect given for a Gaussian turbulence spectrum, by

$$T = e^{-\sigma^2(1-\rho)}. \quad (4)$$

In Eq. (4),  $\sigma^2$  is the variance of the phase fluctuation along a path given by

$$\sigma^2 = A\sqrt{\pi}\langle\mu^2\rangle k^2 R L_0, \quad (5)$$

where  $L_0$  is the outer scale of turbulence,  $R$  is the range,  $\langle\mu^2\rangle$  is the variance of the index of refraction,  $k$  is wavenumber, and the coefficient  $A$  is given by

$$A = 0.5, \quad R > kL_0^2 \quad \text{or} \quad A = 0, \quad R < kL_0^2, \quad (6)$$

$\rho$  is the phase which is a function of  $L_0$ , and  $h$  the maximum transverse path separation, i.e.,

$$\rho = \frac{\sqrt{\pi}L_0}{2h} \text{erf}\left(\frac{h}{L_0}\right), \quad (7)$$

where  $h$  is the maximum transverse path separation, which in the absence of refraction is given by

$$\frac{1}{h} = \frac{1}{2} \left( \frac{1}{h_s} + \frac{1}{h_r} \right), \quad (8)$$

where  $h_s$  and  $h_r$  are the source and receiver heights, respectively, and  $\text{erf}(x)$  is the error function defined by

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt. \quad (9)$$

A typical value for  $L_0$  is the source height. Typical values of  $\langle\mu^2\rangle$  are between  $2 \times 10^{-6}$  and  $10^{-4}$ .

The loss of coherence due to scattering is modeled as an “effective” turbulence using parameter values obtained by best fit with data. Predictions for turbulence-affected ground effect [see Eqs. (3)–(9)] due to a point source near the ground have been compared with the winter wheat data at 10 m range. Allowance for the influence of scattering on ground effect has been made by using effective values of variance of index of refraction and outer scale of turbulence of  $5.0 \times 10^{-4}$  and 0.3 m, respectively, as well as the multiple scattering by stems.

## V. COMPARISON BETWEEN DATA AND PREDICTIONS

### A. Predictions due to combined effect of incoherence, scattering, and foliage

The contributions to attenuation are ground effect, thermal and viscous losses at leaf surfaces, multiple scattering by stems and leaves, and loss of coherence. These effects can be summed to obtain the overall attenuation due to crops and ground. The ground effect for a particular ground surface growing crops was obtained by a ground characterization method.<sup>17,18</sup> A short range vertical level difference measurement is carried out inside crops, and the resulting data are fitted using an impedance model to obtain best fit impedance model parameters.<sup>17,18</sup> The attenuation due to crops is obtained by putting estimated foliage area per unit volume ( $F$ ), measured leaf size ( $a$ ) and measured straight-line propagation path through crops ( $L$ ) into Eq. (1). Multiple scattering effects are calculated using Eq. (2). Loss of coherence is calculated using the specified effective

turbulence parameters in Eqs. (3) to (9). All effects are added together to obtain the total attenuation.

Figure 7(a) shows the measured and predicted level difference (LD) spectra between microphones at 1.0 and 5.0 m from the source. The source and receivers were at height of 0.3 m. Measurements were carried out in August 2011 over approximately 0.5 m high winter wheat crops. The impedance parameters obtained from vertical level difference fitting using the slit pore model<sup>17,18</sup> are flow resistivity of  $100 \text{ kPa s m}^{-2}$  and porosity of 0.27. The solid line represents the data. The dashed line represents the predicted ground effect; the dash-dotted line shows the predicted result of a combination of loss of coherence and attenuation caused by multiple scattering by the stems, and the solid-cross line is the sum attenuation due to scattering-affected ground effect and foliage using Eq. (1) with  $F = 20 \text{ m}^{-1}$  and  $a = 0.008 \text{ m}$ . Figure 7(b) compares measured LD between microphones at 1 and 10 m with the corresponding predictions. The data for these larger ranges are fitted consistently with  $F = 20 \text{ m}^{-1}$  and  $a = 0.008 \text{ m}$ . Foliage effect is more important at the longer range.

## B. Predictions only using foliage attenuation

The major contributions to attenuation are ground effect and thermal and viscous losses due to vegetation. Indeed it is possible to avoid calculating the multiple scattering and loss of coherence effects and to compensate for these effects by using larger values for foliage per unit area and mean leaf size in Eq. (1).<sup>14</sup> Thereby it is possible to obtain reasonable predictions by only adding ground effect to attenuation due to viscous and thermal losses as predicted by Eq. (1). The ground effect for a particular ground surface growing crops was obtained by a ground characterization method.<sup>17</sup> The attenuation due to crops is obtained by putting estimated foliage area per unit volume ( $F$ ), measured leaf size ( $a$ ), and measured propagation path through crops ( $L$ ) into Eq. (1). The effects are added together to obtain the total attenuation.

Figures 8(a) and 8(b) show spectra of the difference in levels measured by the reference microphone at a distance of

1.0 m and microphones at distances of 5.0 and 10.0 m from the source, respectively. The source and receivers were at height of 0.3 m. Measurements were carried out in August 2011 over approximately 0.5 m high winter wheat crops. Also shown are predictions of ground effect and of ground plus crop effects. The impedance parameters obtained from ground characterization using the slit pore model<sup>17</sup> are flow resistivity of  $100 \text{ kPa s m}^{-2}$  and porosity of 0.27. The crops were dry with reduced foliage [see Fig. 3(a)]. The estimated foliage area per unit volume was  $20 \text{ m}^{-1}$  and mean leaf size was 0.012 m. The propagation path length depends on the further microphone position. The agreement between the measured spectra and those predicted by adding ground effect to foliage/stem attenuation using parameters given in the preceding text is good. At lower frequencies, the ground effect is dominant, and there is no crops effect as expected given the thinner stem sizes. At higher frequencies, i.e., above 3–4 kHz, the crops effect is dominant. Lower frequency attenuation is due to ground effect, and high frequency attenuation is due to crops.

Figures 8(c) and 8(d) show spectra of the difference in levels measured over winter wheat crops in May 2012 when the crops were very green and leafy [see Fig. 3(b)]. The reference microphone placed at a distance of 1.0 m and other microphones placed at distances of 5.0 and 10.0 m from the source, respectively. Also shown are ground effect predictions obtained by using two-parameter slit pore impedance for the ground with a flow resistivity of  $200 \text{ kPa s m}^{-2}$  and porosity of 0.2 with the addition of a crops effect attenuation based on Eq. (1) using an estimated foliage area per unit volume of  $50 \text{ m}^{-1}$  and mean leaf size of 0.012 m. The agreement between the data and predictions is good except between 1 and 3 kHz at longer ranges where incoherence due to scattering reduces the ground effect. Both data and predictions in Figs. 8(c) and 8(d) corresponding to wetter greener leafier conditions show higher attenuation above 3 kHz than shown in Figs. 8(a) and 8(b) corresponding to dry crop conditions.

Measurements over winter wheat were carried out again in June 2012 when the crops were neither very green

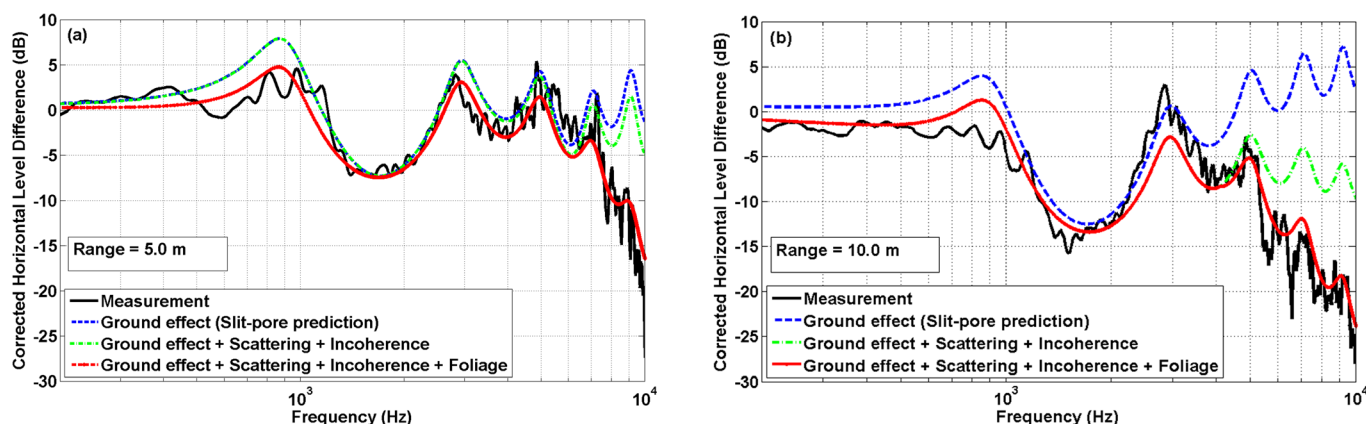


FIG. 7. (Color online) (Data collected in August 2011) Measured spectrum of the horizontal level difference (source and receivers 0.3 m above ground) over 0.5 m high winter wheat crops between receivers at 1 m and (a) 5.0 m and (b) 10.0 m from the source (solid line); predicted ground effect alone, broken line; ground effect plus incoherence plus multiple scattering by stems, broken dotted line; ground effect plus incoherence plus multiple scattering by stems plus viscous and thermal attenuation [Eq. (1) with  $F = 20 \text{ m}^{-1}$  and  $a = 0.008 \text{ m}$ ], solid cross line.



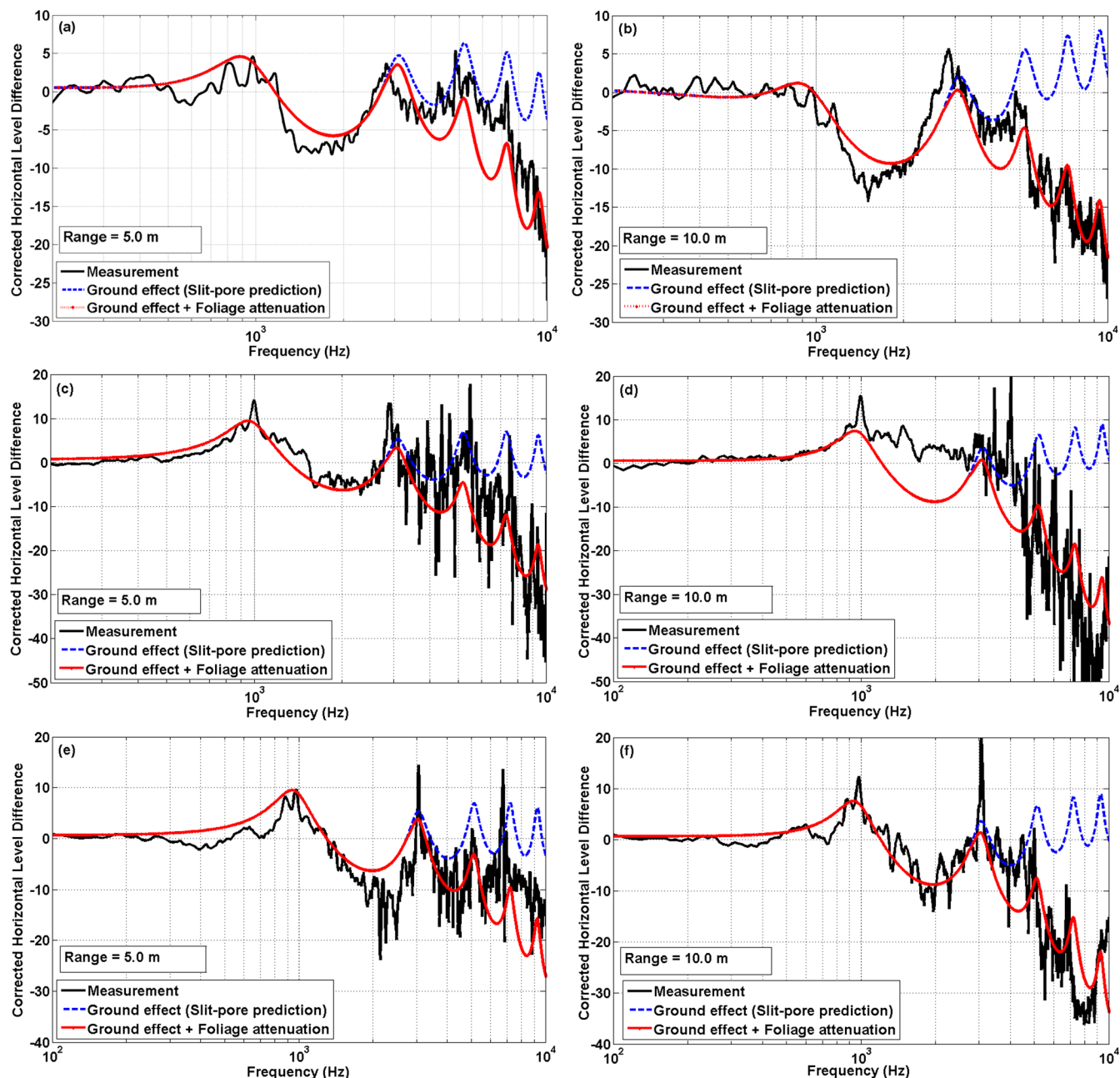


FIG. 8. (Color online) Measured spectrum of the horizontal level difference (source and receivers 0.3 m above ground) over 0.5 m high winter wheat crops between receivers at 1 and 5.0 m and at 1 and 10.0 m from the source (solid line); predicted ground effect alone, broken line; ground effect plus viscous and thermal attenuation, solid cross line. (a) and (b) Data were collected in August 2011; ground impedance given by slit pore model: Flow resistivity =  $100 \text{ kPa s m}^{-2}$ , porosity = 0.27; attenuation predicted by Eq. (1),  $F = 30 \text{ m}^{-1}$ ,  $a = 0.012 \text{ m}$ . (c) and (d) Data collected in May 2012; ground impedance given by slit pore model: Flow resistivity =  $200 \text{ kPa s m}^{-2}$ , porosity = 0.2; attenuation predicted by Eq. (1),  $F = 50 \text{ m}^{-1}$ ,  $a = 0.012 \text{ m}$ . (e) and (f) Data collected in June 2012; ground impedance given by slit pore model: Flow resistivity =  $200 \text{ kPa s m}^{-2}$ , porosity = 0.2; attenuation predicted by Eq. (1),  $F = 40 \text{ m}^{-1}$ ,  $a = 0.012 \text{ m}$ .

nor very dry [see Fig. 3(c)]. Figures 8(e) and 8(f) compare the spectra of the difference in levels measured by the reference microphone at a distance of 1.0 m and microphones placed at distances of 5.0 and 10.0 m from the source, respectively, with predictions of ground effect alone and ground effect plus crops attenuation. The ground effect is predicted using the slit pore model with flow resistivity of  $200 \text{ kPa s m}^{-2}$  and porosity of 0.2. The crops effect is predicted from Eq. (1) with estimated foliage area per unit volume of  $40 \text{ m}^{-1}$  and mean leaf size of 0.012 m. There is good agreement between the measured horizontal level

difference spectra and the predictions of ground effect plus crops effect.

## VI. MITIGATION OF SURFACE TRANSPORT NOISE

Growing demand on transportation, road, and railway networks has resulted in increased levels of annoyance from road traffic and railway noise. The traditional way of reducing noise is to erect a noise barrier that divides the communities and is ineffective for long source-barrier-receiver distances. The main idea being investigated here is to

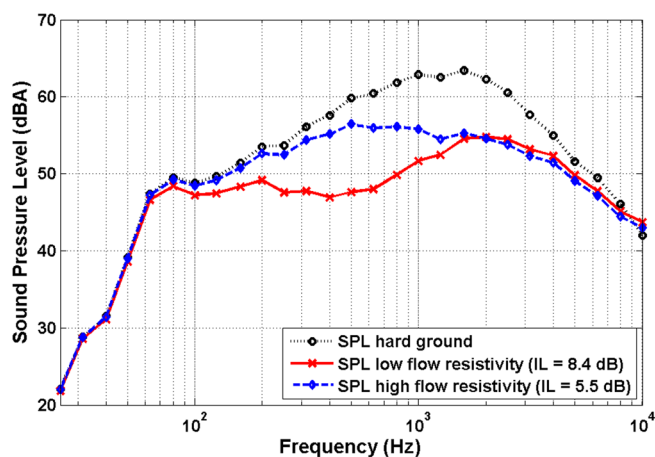


FIG. 9. (Color online) Comparison between predicted A-weighted sound pressure levels over a hard ground, dotted-circle line; a low flow resistivity site (long grass,  $R_s = 104.0 \text{ kPa s m}^{-2}$ ,  $\Omega = 0.36$ ), continuous-cross line; and a high flow resistivity site (arable,  $R_s = 2251.0 \text{ kPa s m}^{-2}$ ,  $\Omega = 0.5$ ), broken-diamond line. The soft ground is assumed to start at a distance of 2.5 m from nearest lane, for two lane urban road at 1.5 m high receiver and at 50 m distance from the nearest lane.

optimize the use of green areas, green surfaces, and other natural elements in urban and rural environments for reducing the noise impact of road and rail traffic. If the ground is acoustically soft, the destructive interference occurs at relatively low frequencies and can be useful for traffic noise attenuation. According to HARMONOISE engineering methods,<sup>19</sup> the A-weighted traffic noise source spectrum has a peak at 1 kHz. So acoustically soft ground that has a broad ground effect centered at 1 kHz could give useful traffic noise attenuation. The sound attenuation due to different soft ground types are explored here.

### A. Replacing hard ground with soft ground

Short range ground characterization along with an appropriate impedance model and geometry information enables prediction of sound propagation over a ground surface.<sup>17</sup> An extensive amount of ground characterization for different types of ground surfaces has been carried out.<sup>17</sup> The impedance parameters obtained for different ground types<sup>18,20–22</sup> with acoustical properties modeled by the slit pore or slit pore layer impedance models have been used to predict the excess attenuation spectra for various traffic sources and receiver locations. The source spectra for a two-lane urban road are given by HARMONOISE.<sup>19</sup> The insertion loss for a given ground surface is calculated by using these source spectra along with predicted excess attenuation for a given ground type.<sup>20</sup>

The acoustical effects of types of grassland are predicted to depend on the (fitted) flow resistivity values. Higher traffic noise reductions are predicted if the ground has relatively low flow resistivity. Flow resistivity increases with compaction. Ground surfaces that have been compacted, for example, by frequent mowing, rolling, or heavy wheeling are likely to have higher flow resistivity.

Figure 9 compares the SPL spectra due to a two-lane urban road (95% cars, 5% heavy vehicles, mean speed 50 km/h) at a 1.5 m high receiver 50 m from the road predicted for hard ground, an example low flow resistivity ground and an example high flow resistivity ground. Up to 2 kHz the lower resistivity grounds provide extra reduction in levels.

Calculations carried out in context of HOSANNA<sup>23</sup> project guidelines consider only two receiver heights, i.e., 1.5 and 4.0 m and a range of 50 m. These show that the insertion loss due to porous ground surfaces is less for the higher receiver height of 4.0 m. This is a consequence of the fact that the ground treatments are more effective at near grazing angles. Similarly the attenuation performance of porous ground improves as the distance between the source and receiver increases. Also the HOSANNA study constrained the nearest edge of ground treatments to be 2.5 m from the source. The effectiveness for higher receiver heights can be improved if the treatment is moved closer to the source.

### B. Crops on soft ground

As discussed previously, data obtained over crops have been fitted using an empirical attenuation formula based on Aylor's data<sup>1,2</sup> for dense large leaf corn crops. Analysis of data for sound transmission loss through smaller leaf winter wheat crops (Sec. III) makes it possible to predict the extra attenuation (i.e., in addition to that due to soft ground effect) due to winter wheat foliage using the same empirical formula.

The reductions in noise in  $\text{dB m}^{-1}$  calculated for two types of 1 m high crops (winter wheat and dense corn) with six types of soft ground assuming the configuration depicted in Fig. 10 are listed in Table I. The dense corn crop is characterized by a leaf area per unit volume of  $6.3 \text{ m}^{-1}$  and a mean leaf size of  $0.0784 \text{ m}$ . For winter wheat, the corresponding values are  $30 \text{ m}^{-1}$  and  $0.012 \text{ m}$ , i.e., the winter wheat is assumed to have a higher foliage area per unit volume but much smaller leaves than corn.

The overall attenuation is calculated as the sum of that due to ground effect and the attenuation along those parts of the direct paths from the vehicle sources to the receivers that

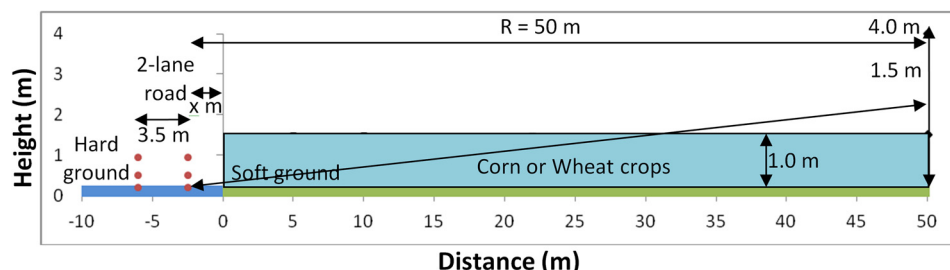


FIG. 10. (Color online) Cross section of a two lane urban road with nearby 1.0 m high crops.

TABLE I. Calculated reductions of noise for a two lane urban road after replacing hard ground by soft ground and cultivating 1 m high winter wheat or dense corn crops.

Surface impedance description	Insertion loss (dB) compared with hard ground – 2 lane road					
	Ground alone		Ground + wheat		Ground + dense corn	
	$H_r = 1.5$ m	$H_r = 4$ m	$H_r = 1.5$ m	$H_r = 4$ m	$H_r = 1.5$ m	$H_r = 4$ m
No. 22 pasture	6.3	2.6	6.7	2.9	10.1	6.0
No. 24 arable	5.5	1.7	6.0	2.2	9.5	5.7
No. 28 sports field	6.0	2.4	6.6	2.7	10.0	5.8
No. 16 lawn	8.7	3.3	9.6	3.7	14.2	8.0
No. 18 arable	8.4	3.3	9.4	3.6	14.4	7.9
No. 41 long grass	8.6	3.2	9.5	3.6	14.7	8.0

pass through the crop (see Fig. 10). The combination of high flow resistivity ground and small leaf crop is predicted to have little acoustical merit. On the other hand, combinations of low flow resistivity ground and dense large leaf crops are predicted to give a total attenuation of between 9 and 13 dB at the 1.5 m high receiver of which between 1 and 5 dB is contributed by the crops. The corresponding predicted total attenuations at the 4 m high receiver are between 2.5 and 7 dB of which between 0.3 and 4.5 dB are contributed by crops. The 1 m high corn crop is predicted to offer nearly 3 dB additional attenuation at the 4 m high receiver.

Figure 11 compares the SPL spectra due to a two-lane urban road at a 1.5 m high receiver 50 m from the road (see Fig. 11) predicted for hard ground, an example soft ground (No. 16, Lawn, see Table I), soft ground plus winter wheat crops and soft ground plus dense corn. Dense corn effect start at lower frequencies due to thicker stem and large leaf size as compared to winter wheat crops, which have thin stem and leaves.

The attenuation due to crops depends on the propagation path through crops. As the height of the receiver increases, the propagation path through crops decreases as shown in Fig. 10. It means that as the height of the receiver increases

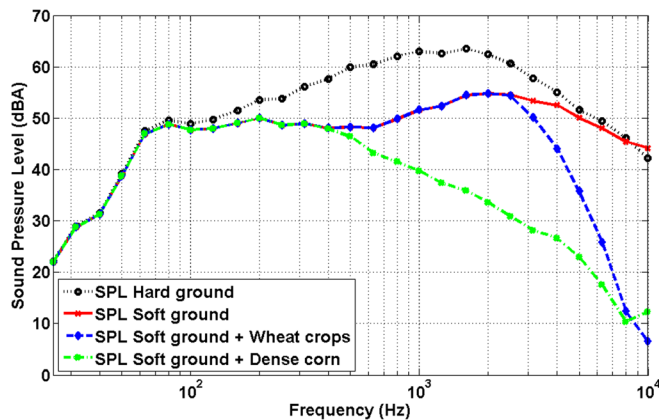


FIG. 11. (Color online) Comparison between predicted A-weighted sound pressure levels over a hard ground, dotted-circle line; soft ground Nordtest Lawn site 16 ( $R_s = 176.0 \text{ kPa s m}^{-2}$ ,  $\Omega = 0.50$ ), continuous-cross line; soft ground plus winter wheat ( $F = 30 \text{ m}^{-1}$ ,  $a = 0.012$ ), broken-diamond line; and soft ground plus dense corn ( $F = 6.3 \text{ m}^{-1}$ ,  $a = 0.0784$ ), broken-dotted-asterisk line. The soft ground starts at a distance of 2.5 m from nearest lane, for two lane urban road at 1.5 m high receiver and at 50 m from the nearest lane.

or the height of the crops decreases, the attenuation effect due to crops decreases and vice versa.

The insertion loss has been calculated also for longer ranges<sup>20,23</sup> such as 100, 235, and 500 m. The crops effect is predicted to increase with the range because the propagation path through crops increases along with the soft ground effect. However, at these longer ranges, it is likely that the propagation would be affected more by meteorological effects such as upward refraction, which would limit the achievable attenuation due to soft ground and crops.

## VII. CONCLUSIONS

A series of measurements have been carried over winter wheat crops. Vertical level difference was measured by clearing crops to characterize the ground surface on which crops were growing. However, later it was found that vertical level difference measurements can be carried out inside crops without clearing the area. Horizontal level difference data were used to study the sound propagation through crops. It is concluded that the sound attenuation by crops occurs due to multiple scattering between the stems and leaves, loss of coherence, and viscous and thermal losses due to foliage. However, the major contribution to attenuation due to crops is due to viscous and thermal losses, which can be predicted by using an empirical formula [see Eq. (1)]. This may be termed the crops effect. At lower frequencies, ground effect is dominant and there is little or no crops effect. At higher frequencies above 3–4 kHz, the crops effect is dominant. It was also found that the ground and crops effects can be treated independently and can be added to obtain the total effect. Green leaf crops result in more attenuation than dry crops with fallen leaves.

Predictions of sound propagation through crops have been carried out by adding ground effect and acoustical effects of the crops. The acoustical properties of a particular ground surface growing crops were obtained by a ground characterization method.<sup>17</sup> The attenuation due to crops is obtained by adding viscous and thermal losses, multiple scattering effects, and loss of coherence to obtain the total attenuation. The major contributions to attenuation are ground effect and thermal and viscous losses due to vegetation. Indeed it is possible to avoid calculating the multiple scattering and loss of coherence effects and yet to obtain reasonable predictions by only adding ground effect to



attenuation due to viscous and thermal losses using larger values for foliage per unit area and mean leaf size in Eq. (1).

The reductions in noise levels by replacing hard ground with soft ground have been investigated. Useful insertion losses result from replacing hard ground with different types of acoustically soft ground along the road sides. It is predicted that replacing 47.5 m of hard ground by any kind of soft ground gives at least 5 dB insertion loss at a 1.5 m high receiver 50 m from the road. A low flow resistivity ground surface can give up to 3 dB more traffic noise attenuation than a high flow resistivity ground. Grassland left untouched and allowed to grow wild improves traffic noise attenuation performance. Cultivating the intervening ground (between the road and receivers) and adding crops such that they block direct line of sight between the noise source and the receiver (at least partially) can result in an additional IL of between 3 and 5 dB. The noise attenuation due to crops depends on the length of the sound propagation path through the crops.

These predictions are likely to be valid only for the relatively short ranges up to 50 m considered. At longer ranges, meteorological effects are likely to be more important than ground and crops effects.

## ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant No. 234306, collaborative project HOSANNA. The authors are grateful also to Rothamsted Research for allowing the measurements at Butt Close.

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